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THE FIRST DETECTION OF NEAR-INFRARED CN BANDS IN ACTIVE GALACTIC NUCLEI: SIGNATURE OF STAR FORMATION

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ABSTRACT

We present the first detection of the near-infrared CN absorption band in the nuclear spectra of active galactic nuclei (AGN). This feature is a recent star formation tracer, being particularly strong in carbon stars. The equivalent width of the CN line correlates with that of the CO at 2.3 μm as expected in stellar populations (SP) with ages between $\sim$0.2 and $\sim$2 Gyr. The presence of the 1.1μm CN band in the spectra of the sources is taken as an unambiguous evidence of the presence of young/intermediate SP close to the central source of the AGN. Near-infrared bands can be powerful age indicators for star formation connected to AGN, the understanding of which is crucial in the context of galaxy formation and AGN feedback.

Subject headings: galaxies: stellar content – galaxies: active – galaxies: nuclei

1. INTRODUCTION

It is widely known that circumnuclear star formation is commonly detected in active galactic nuclei (AGN) (e.g. Sturm et al. 1999; Contini et al. 2002; Storchi-Bergmann et al. 2005; Shi et al. 2006). In fact, in the last years, increasing observational evidence has confirmed that nuclear/circumnuclear starbursts (SBs) coexists in objects harboring an AGN (e.g. Mizutani et al. 1994; Imanishi & Dudley 2000; Imanishi 2002; Rodríguez-Ardila & Viegas 2003; Imanishi & Wada 2004). For example, Storchi-Bergmann et al. (2000) in a study of a sample of 20 Seyfert 2 (Sy 2) galaxies find out that about 50% of the sources have young to intermediate-aged ($\sim$ 1 Gyr) nuclear starbursts and that 30% of the galaxies display a recent burst of star formation ($t < 500$ Myr, results confirmed by Gonzlez-Delgado et al. 2001). Currently, it is thought that both the active nucleus and the starburst might be related to gas inflow, probably triggered by an axis-asymmetry perturbation like bars, mergers or tidal interactions (Shlosman et al. 1989, 1990; Maiolino et al. 1997; Knapen et al. 2000; Fathi et al. 2006). This gives support to the so-called AGN-starburst (AGN-SB) connection (Norman & Scoville 1988; Terlevich et al. 1990; Heckman et al. 1997; Gonzalez-Delgado et al. 1998; Veilleux 2000; Ferrarese & Merritt 2000; Heckman 2004). This connection, however, could be incidental, as many Seyferts do not show any evidence of starburst activity (e.g. Filippenko et al. 1993) and optical spectroscopic studies of large samples do not indicate that starburst are more common in Seyferts than in normal galaxies (Pogge 1989). One difficulty in establishing the AGN-SB connection further is that tracing starbursts reliably is difficult (Oliva et al. 1995). In the NIR region, except for a few indicators such as the methods based on the CO(2-0) first overtone or the Brγ emission (e.g. Origlia et al. 1993; Oliva et al. 1995), the detection of spectral features allowing the identification and dating of young stellar populations (SP) in the inner few tens of parsecs of AGN remains difficult. To understand the physics of the above connection is particularly important for galaxy formation theories, as AGN activity is advocated as regulator of star formation in massive protogalaxies, the so-called AGN feedback phenomenon (Silk & Rees 1998; Binney 2004; Croton et al. 2006; Bower et al. 2006).

In this line of thought, the evolutionary population synthesis calculations presented by Maraston (2005, hereafter M05), by including empirical spectra of carbon and oxygen rich stars (Lancon & Wood 2000), are able to foresee the presence of molecular features like CH, CN and C_2. They arise in young/intermediate SP and their spectral signatures are particularly enhanced in the NIR. Of particular importance are the CN bands, which arise according to the models, from stars with ages in the range $0.3 \leq t \leq 2$ Gyr and are attributed to stars in the thermally pulsing asymptotic giant branch (TP-AGB) phase. It means that their detection can be taken as an unambiguous signature of the presence of young/intermediate SP in a well-constrained age, signaling the occurrence of SB activity. In the optical, CN bands are common in the spectra of globular clusters (e.g. Smith et al. 1989; Cohen 1999a,b; Smith & Briley 2006) but have been rarely reported in AGN. To our knowledge, the object showing

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the presence of this feature is the Sy 2 galaxy NGC 7679, where Gu et al. (2001) report extremely weak optical CNλ4200 Å. However contrary to the NIR, optical CN reveals old SP rather than young/intermediate-age ones (e.g. Storchi-Bergmann et al. 2000). Here, we report the first observation of the 1.1μm CN band predicted by the M05 models in a comprehensive sample of Seyfert galaxies, demonstrating the usefulness of the NIR spectral region as an important tool to investigate recent star formation episodes.

This paper is structured as follows: in Section 2 we describe the data. The results are presented in Section 3. A discusion of the results is made in Section 4. Final remarks are given in Section 5.

2. THE DATA

The galaxy spectra chosen for this work are the ones presented by Riffel et al. (2006, hereafter RRP06). The NIR spectra were obtained at the NASA 3 m Infrared Telescope Facility (IRTF). The SpeX spectrograph (Rayner et al. 2003), was used in the short cross-dispersed mode. A 0.8”×15” slit was employed giving a spectral resolution of 360 km s^{-1}. For more details see RRP06. A rapid inspection to the left panels of Figs. 1 to 8 and Fig. 12 of RRP06 shows that a significant fraction of objects display a deep prominent broad absorption feature starting at $\sim$1.1μm and extending up to 1.15μm in some sources (see, for example, NGC 1097, NGC 1144 and NGC 1614). In other objects such as Mrk 1066, NGC 5953 and NGC 7714, it is considerably narrower but still deep and strong. Almost invariably, the galaxies displaying the 1.1μm absorption also present strong CO 2.3μm bands and a H-continuum dominated by several absorption lines. The CaT at 0.8 μm is also prominent in these objects. Moreover, these sources were classified as Sy 2/SB except Mrk 334 and NGC 1097, considered by RRP06 as Sy 1. The invariably association with CO bands and the CaT triplet allowed us to consider that the 1.1 μm absorption could indeed be associated to stellar population although no previous observational report of this feature were found in the literature.

Columns 2 and 3 of Table 1 list the names and AGN type, respectively, of the galaxies where a clear evidence of the 1.1μm absorption was found.

TABLE 1
The sub-sample of RRP06 sample that shows the presence of the NIR CN molecular band. Some of the galactic properties and the equivalent widths of CN band and CO line are also presented.

ID (1)	Galaxy (2)	Type (3)	r (pc)[a] (4)	W_{CN} 1.1μm (mag) (5)	W_{CO} 2.29μm (mag) (6)
1	Mrk 334	Sy1	340	0.063±0.001	0.047±0.003
2	NGC 34	SB/Sy2	230	0.082±0.001	0.117±0.001
3	NGC 591	Sy2	206	0.055±0.001	0.098±0.009
4	Mrk 573	Sy2	267	0.046±0.002	0.057±0.005
5	NGC 1097	Sy1	58	0.019±0.002	0.078±0.005
6	NGC 1144	Sy2	447	0.062±0.002	0.077±0.009
7	Mrk 1066	Sy2	186	0.045±0.001	0.097±0.007
8	NGC 1614	SB	154	0.085±0.002	0.139±0.007
9	NGC 2110	Sy2	121	0.066±0.001	0.033±0.001
10	NGC 3310	SB	56	0.052±0.002	0.080±0.009
11	NGC 5929	Sy2	193	0.050±0.002	0.082±0.009
12	NGC 5953	Sy2	165	0.041±0.002	0.104±0.002
13	NGC 7682	Sy2	179	0.036±0.001	0.079±0.009
14	NGC 7714	H II	115	0.081±0.002	0.098±0.021

[a]Radius of the integrated region.

3. RESULTS

The association of the 1.1 μm absorption with the CN molecule was evident after comparing our spectra with Fig. 15 of M05, where a grid of synthetic spectra that include the effects of TP-AGB stars is shown. In these models, the dominant feature in the interval 0.9$-$1.4 μm is a strong absorption centred at 1.1 μm and attributed to CN. Models that do not include the TP-AGB population do not display the absorption. The M05 models also show that the strength of the CN absorption is a function of age and metallicity (Fig. 15 of M05). Other features present in the templates are also easily recognized in our data, including the overall shape of the continuum emission and the CaT and CO bands, particularly in the SB galaxies.

The upper left panel of Fig. 1 shows a comparison of a 1 Gyr and solar metallicity template of M05 with our data, confirming that the 1.1 μm absorption is due to CN, associated to TP-AGB stars in the galaxies. No previous report of the CN1.1μm band in extragalactic objects was made before. Our result points out to the presence of a significant young/intermediate stellar population, with ages between 0.3 and 2 Gyr in the objects listed in Tab. 1.

In order to properly quantify the strength of the CN 1.1μm we need to subtract the emission lines of He I λ1.0830μm and Paγ 1.0938 μm that affect the band. Therefore, we have modelled these emission lines constraining the Paγ width and flux to those of Paβ 1.2820 μm using the calculations by Hummer & Storey (1987) for their intrinsic line ratio values. For the He I, we have adjusted a gaussian to the emission line profile. It is a reliable approximation because the helium emission line is located near the blue end of the CN absorption band. As for the He I, in the spectrum of Mrk 334 we have adjusted a gaussian to the O I λ1.1287μm emission line. The LINER software (Pogge & Owen 1993) was used for this purpose. A sample of the results of this process is presented in Fig. 2.

With a clear CN band, free of contamination of the emission lines, we proceed to measure the equivalent width (W) of the CN band. The continuum was linearly adjusted using the points between 1.0445μm and 1.0580μm as representative of the continuum at the left side of the CN band and for the right side we defined the points between 1.2160μm and 1.2385μm. The band widths were defined using the Maraston models, as being between 1.0780μm and 1.1120μm. We also include, for comparison, the W of the CO 2.2980 μm line of the 2.3μm CO band, measured from the galaxy spectra, taking as the line width the points 2.2860μm and 2.3100 μm for the band width and a continuum defined as a spline using points free from emission/absorption lines in the interval between 2.2350μm and 2.3690μm. The W_{CN} and W_{CO} measured values are listed in column 7 and 8 of Tab. 1. Here the LINER software was also used.

4. DISCUSSION

The NIR CN absorption band is particularly enhanced in carbon stars, where there is residual carbon that is not binded with oxygen in CO molecules. As carbon stars are only produced after the third convective dredge-up

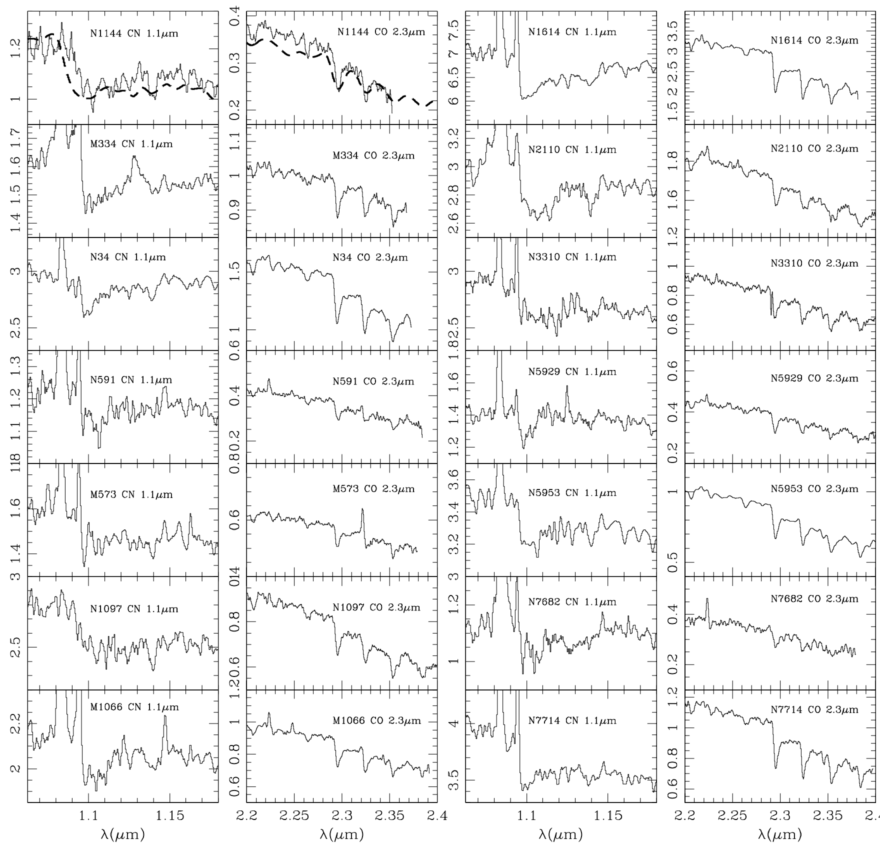

FIG. 1.— Zoom around the 1.1μm CN and 2.2μm CO bands for the galaxies which clearly shows the presence of the 1.1μm CN band. In the top left panel we show the predicted 1.1μm CN band of a population with 1 Gyr and solar metallicity (M05) overploted at the NGC 1144 spectrum and the CN molecular band lines observed in our sample of galaxies. The ordinate is the flux in units of $10^{-15}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$.

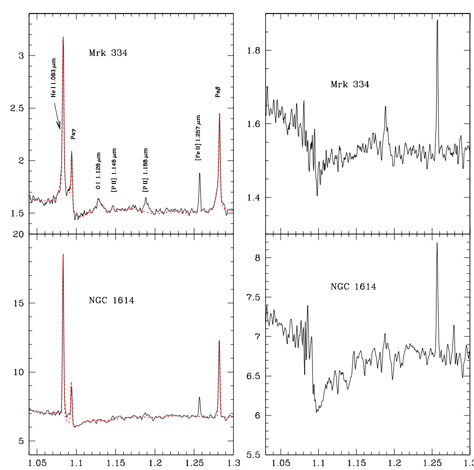

FIG. 2.— Model for the emission lines around the CN absorption band. At the left side the full line is the spectrum of the galaxy and the modelled lines and continuum are represented by the dotted lines. At the right side the CN band free from the emission spectra is presented. The ordinate is the flux in units of $10^{-15}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$.

along the TP-AGB phase (e.g. Iben & Renzini 1983), their features are a clear indicator of SP rich in these stars. This constrains the age of such SP to be within the narrow range 0.3 to 2 Gyr (M05).

In order to check if our observations are actually consistent with this claim, we compare the observed strength of CN and CO with the Maraston's model predictions. Note that the CO alone would not be a useful age indicator because this band is not only strong in TP-AGB stars or red-supergiants, but also in old RGB stars (e.g. Ivanov et al. 2000; Imanishi & Alonso-Herrero 2004). Fig. 3 plot the values of simple stellar populations (SSPs) with ages between 0.2 and 3 Gyr and metallicities from 1/50 to twice solar.

Fig. 3 confirms that the observed values are indeed consistent with the model predictions in this age range, and that the strengths of the two bands are correlated (R^2= 0.66). The CO band is also present in TP-AGB spectra (cfr Fig. 16 of M05), which explains the correlation between the W of CN and CO. Interestingly, the data can be separated into two main groups according to the chemical composition. One group (NGC 34, Mrk 573, NGC 1144, NGC 3310, NGC 7682 and NGC 7714) has the light dominated by stars with solar/half solar metallicity. A second group (NGC 591, NGC 1097, Mrk 1066, NGC 5929 and NGC 5953) harbors SP with high metallicity, and just two objects are consistent with low metallicity. A detailed analysis of the ages and metallicities of our sample is postponed to another paper (Riffel et al., *in preparation*).

Optical stellar population synthesis carried out by Raimann et al. (2003) in a sample of Seyfert galaxies,

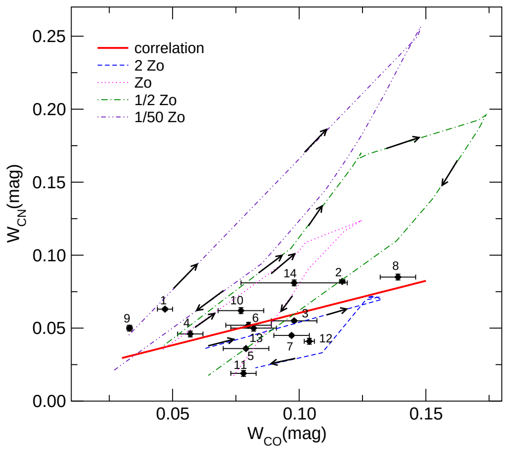

FIG. 3.— CN equivalent width *versus* CO equivalent width. The observed values are represented by full circles. Numbers identify the sources according to column 1 of Tab 1. Models are indicated on the labels. The arrows indicate the age sequence of the models ranging from 0.2 Gyr to 3 Gyr.

four of them common to our sample (Mrk 573, Mrk 1066, NGC 2110 and NGC 5929) reveals that old population (10 Gyr) dominates the inner few hundred parsecs. The integrated regions of our NIR spectra are similar to that of Raimann et al. (2003). As shown by our results, for these same objects the NIR spectra display unambiguous signature of young/intermediate SP with ages between 0.3 and 2 Gyr. It means that the J-band provides complementary information not detected in the optical. An additional advantage of the CN is that it is located near the center of the *J*-band allowing its observation in a wide range of redshifts ($z \lesssim 0.18$). The CO band instead is located near the red end of the K-band thereby allowing only observations of sources with redshifts smaller than 0.03.

5. FINAL REMARKS

We present the first detection of the 1.1μm CN band in the inner 300 pc of an AGN. The presence of the CN at 1.1μm in the spectrum can be taken as an unambiguous evidence of recent star formation, in particular it is associated with the presence of bright carbon stars. We have compared the observed values with predictions of SP including the contribution of carbon stars. We find a nice consistency of observed and predicted values for ages around 1 Gyr. This supports the claim that the NIR CN band is suggestive of young/intermediate age SP. Its use as age indicator is particularly adapt to AGN-hosts, where dust reddening can complicate seriously the use of optical bands. Moreover, since these molecules are enhanced in SP spanning a narrow age range, their detection is relatively robust against the age/metallicity degeneracy.

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